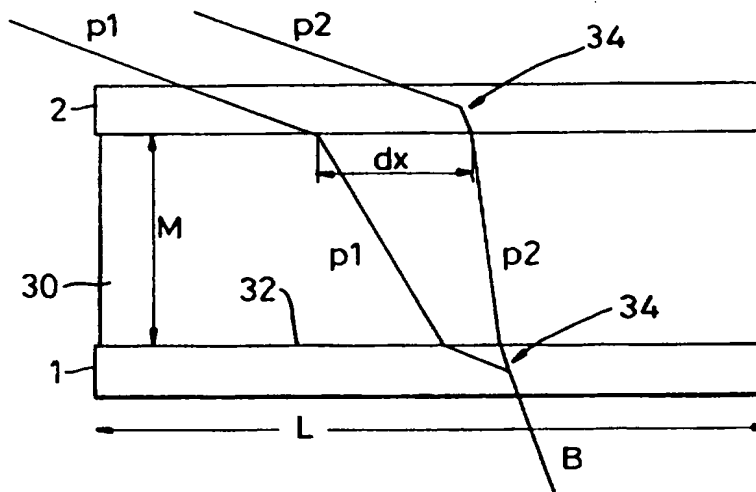




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(54) Title: HOLOGRAPHIC OPTICAL DEVICE AND METHOD OF MANUFACTURE



(57) Abstract

The invention provides an optical element comprising a first hologram (1) and a second hologram (2) separated by an intervening medium (30). The holograms (1, 2) have the same diffraction spacing and refractive index, but the first hologram (1) has an efficiency about one-half that of the second hologram (2), preferably about 50 % and >95 %, respectively. The geometry and the refractive index of the intervening medium (3) are such that an input beam (B) of mixed light undergoes diffraction and refraction to produce output beams (p1, p2) which combine in a controllably self-cancelling manner. Methods for the production of this element are also described.

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1

2 TITLE OF THE INVENTION

3

4 HOLOGRAPHIC OPTICAL DEVICE AND METHOD OF MANUFACTURE

5

6 FIELD OF THE INVENTION

7

8 This invention relates to optical devices for producing
9 non-fringing destructive interference of light, and to
10 a method of making and using the same.

11

12 BACKGROUND TO THE INVENTION

13

14 Light moves through space as an electromagnetic wave.
15 The wave can be envisioned as a series of peaks and
16 troughs moving continuously along a given path at a
17 given frequency. Interference occurs when two waves
18 pass through the same region of space at the same time.
19 Interference between waves can be both constructive and
20 destructive. Constructive interference occurs when the
21 peaks (and troughs) of two waves meet each other at the
22 same time and overlap. These waves are said to be in
23 phase and when this happens the amplitude of the waves
24 at the point of overlap is increased.

25

26 Destructive interference occurs when the peaks of one
27 light wave meet and overlap with the troughs of a
28 second light wave. When the peaks and troughs meet

1 each other they cancel and the wave is said to be phase
2 cancelled. A perfectly phase cancelled wave has no
3 electromagnetic energy.

4
5 Both constructive and destructive interference of light
6 can be demonstrated by a double split experiment
7 whereby light from a single source falls on a screen
8 containing two closely spaced slits. If a viewing
9 screen is placed behind the first screen, a series of
10 bright and dark lines will be seen on the viewing
11 screen. This series of lines is called an interference
12 pattern.

13
14 The bright lines of an interference pattern are areas
15 of constructive interference, and the dark lines are
16 areas of destructive interference. The pattern is
17 generated as waves of a particular wavelength enter the
18 two slits. The waves spread out in all directions
19 after passing through the slits so as to interfere with
20 each other. If a wave from each slit reaches the
21 center of the viewing screen, and these waves travel
22 the same distance before they hit the screen, they will
23 be in phase and a bright spot indicating constructive
24 interference will occur at the center of the viewing
25 screen. There will also be constructive interference
26 at each point the paths of two light rays differ by one
27 wavelength or multiples of one wavelength. However, if
28 one ray travels an extra distance of one-half a
29 wavelength or some multiple of a half wavelength, the
30 two waves will be exactly out of phase when they reach
31 the screen, and so a dark band will appear in the
32 interference pattern indicating destructive
33 interference. Thus, you get a series of bright and
34 dark lines in the interference pattern called
35 "fringes".

36

1 The double slit experiment is one method of producing
2 destructive interference. However, only a small
3 portion of the source light is cancelled. Another
4 method of producing destructive interference of light
5 has been accomplished by using a beam splitter,
6 mirrors and a laser. This type of device is often
7 referred to as an interferometer.

8
9 An interferometer works on the following principle. A
10 laser is used in conjunction with a beam splitter to
11 cause the laser beam to split in two, with a certain
12 percentage of light taking one path and a certain
13 percentage of light taking another path. The path of
14 one of the split beams can be delayed by using amovable
15 mirror such that the beam can be reflected back
16 parallel with the unreflected beam by variable path
17 lengths which can differ by fractions of a wavelength.
18 The degree of cancellation depends on the "coherence
19 length" of the laser and the narrowness of the
20 chromatic line. For these reasons, a laser of
21 extremely high quality is required to produce a
22 significant degree of cancellation. However, no laser
23 produces purely monochromatic light and a fringe is
24 produced regardless of the degree of cancellation. In
25 order to produce a perfectly phase-cancelled
26 non-fringing collinear beam, destructive interference
27 must occur over all incident wavelengths and phases of
28 the entire bandwidth of the incident light source, all
29 of the light rays emitted by the source must be
30 parallel, each photon in the beam must be paired with
31 another photon having the exact same wavelength, and
32 the path lengths of half of the photons must be delayed
33 by a multiple of exactly one half wavelength with
34 respect to the path lengths of their paired photon
35 partners.
36

1 No conventional arrangement can achieve this result.
2 Although a pair of semi-silvered mirrors could be
3 placed such that one specific wavelength could be made
4 to interfere it cannot be correct for all wavelengths.
5 A refractive element could be used to adjust the delay.
6 However, as this only works for non-zero incident
7 angles, the result would be that each wavelength would
8 be travelling along non-parallel paths whose angle can
9 only be increased by the mirrors so the beam could
10 never form a collinear beam and so individual photons
11 can never pair.

12
13 Accordingly, it is an object of the invention to
14 provide a highly efficient optical device which will
15 produce an output beam which is non-fringing, collinear
16 and phase cancelled such that: (a) destructive
17 interference occurs for all incident wavelengths and
18 phases over a bandwidth of at least 1 % plus or minus
19 the center wavelength of a coherent light source such
20 as a laser; (b) all of the output beam's light rays
21 are parallel; (c) each photon in the output beam is
22 paired with another photon having the exact same
23 wavelength; and, (d) the path lengths of half of the
24 photons are delayed by a multiple of exactly one half
25 wavelength with respect to the path lengths of their
26 paired photon partners.

27

28 SUMMARY OF THE INVENTION

29

30 The invention achieves the above-described object and
31 other objectives in the following way:

32

33 An optical device is provided which consists of a
34 holographic element ("hologram") and a refractive
35 optical material of a specifically selected refractive
36 index. The hologram is constructed with a diffraction

1 grating that will induce a wavelength-dependent angle
2 of diffraction for an incident optical beam of a given
3 entry angle. The assembly of the hologram and
4 refractive optical material are such that the
5 wavelength-dependent variation in refraction angle
6 induced by the refractive material will be equal and
7 opposite the wavelength-dependent variation in
8 diffraction angle induced by the hologram such that the
9 angles mutually cancel for each wavelength of the
10 incident optical beam.

11

12 In another embodiment, the previously described optical
13 device is combined with a second hologram such that the
14 optical device consists of two holograms and an
15 intervening (refractive) optical material. Both
16 holograms are constructed with similar diffraction
17 gratings that will induce the same wavelength-dependent
18 angle of diffraction for an incident optical beam of a
19 given entry angle and both holograms are constructed
20 with the same average refractive index. However, each
21 hologram has a predetermined efficiency which is
22 different from the efficiency of the other hologram.
23 The first hologram is preferably about 50% efficient or
24 half as efficient as the second hologram and the second
25 hologram is preferably close to 100% efficient.

26

27 The first hologram is positioned parallel to and
28 spatially separated from the second hologram by an
29 intervening optical material. The intervening optical
30 material is essentially sandwiched by the two
31 holograms. The intervening optical material has a
32 specifically selected refractive index which is
33 different from the average refractive indices of the
34 holograms. The angle of refraction induced by the
35 intervening optical material is also wavelength
36 dependent.

1 By establishing a particular refractive index for the
2 intervening optical material, a wavelength-dependent
3 variation in refraction angle induced by the
4 intervening optical material can be made equal and
5 opposite to the wavelength-dependent variation in
6 diffraction angle induced by the first hologram such
7 that the angles mutually cancel for each wavelength of
8 an incident optical beam having a given entry angle for
9 the first hologram of the optical device.

10

11 Because the first hologram is close to 50% efficient,
12 approximately 50% of the incident optical beam will
13 pass through the hologram undiffracted and
14 approximately 50% of the beam will be diffracted such
15 that two beams will be produced by the first hologram.
16 Both beams will traverse the intervening optical
17 material and impinge upon the second hologram at
18 different angles. The diffracted beam will pass
19 through the second hologram affected only by the change
20 in refractive index whereas the undiffracted beam will
21 interact with the diffraction grating of the second
22 hologram and be diffracted at an angle such that both
23 beams will exit the second hologram parallel to each
24 other.

25

26 By small adjustments of the second hologram, the two
27 exit beams can be made to overlap and the originally
28 undiffracted beam can be intercepted by the second
29 hologram such that it takes a path some multiple of a
30 half wavelength different from the path of the
31 originally diffracted beam. The combined beam will be
32 phase cancelled for all incident wavelengths and phases
33 over a bandwidth of at least 1% plus or minus the
34 center wavelength of the incident optical beam.

35

36 Both the overall delay of the diffracted beam and the

1 overall efficiency of diffraction for the holograms can
2 be adjusted by simply changing the angle of incidence
3 on the first hologram. As the angle of incidence is
4 changed, a greater or lesser percentage of the incident
5 light can be cancelled. The fundamental difference
6 between this effect and that of a simple fixed delay on
7 one of the beams is that as the angle of the total
8 element becomes aligned with the ideal, a greater
9 percentage of the incident light will pass through the
10 defined path. All of the light passing through the
11 defined path will result in a perfect cancellation.
12 So, whereas in a conventional interferometer a series
13 of fringes will be seen, the output of the element as
14 described in this invention will produce a single
15 fringe or beam with a greater or lesser percentage of
16 cancellation proportional to the amount of the incident
17 beam allowed to take the prescribed path.

18

19 Another aspect of the invention includes methods for
20 producing the previously described optical device. In
21 the production of the device, two lasers are used to
22 generate a mixed beam of collinear light consisting
23 essentially of two different wavelengths. The mixed
24 beam is directed at one of the holograms at a given
25 entry angle such that two diffracted beams exit the
26 hologram at different angles and project onto a
27 photo-sensor array a distance L from the exit side of
28 the hologram. The distance between the projection
29 points of the two diffracted beams is measured at the
30 array.

31

32 An intervening optical material having a long dimension
33 equal to L and a selected initial refractive index is
34 positioned between the photo-sensor array and a test
35 photopolymer which has the same average refractive
36 index as the hologram such that its long dimension is

1 perpendicular to the test photopolymer and the array.
2 The same mixed beam is directed at the test
3 photopolymer such that two exit beams are projected by
4 the intervening optical material onto the array. The
5 refractive index of the intervening optical material is
6 then adjusted by polymerization. As the refractive
7 index of the intervening optical material changes, the
8 distance between the projection points of the refracted
9 beams changes. The polymerisation of the intervening
10 optical material is stopped at that point when the
11 displacement between the projection points of the
12 refracted beams measures the same as the displacement
13 between the projection points of the diffracted beams.
14
15 The intervening optical material is then secured to the
16 first hologram such that its short dimension is
17 perpendicular to the hologram. A second hologram, twice
18 as efficient as the first hologram, is positioned at
19 the face of the intervening optical material opposite
20 the first hologram. An incident optical beam having a
21 suitable entry angle is directed at the first hologram
22 so that two exit beams are produced by the second
23 hologram. Slight rotational and lateral adjustments of
24 the second hologram are made until the beams overlap
25 and a position of maximum cancellation is achieved.
26
27 The optical device described above overcomes the
28 limitations associated with interferometers in that it
29 can produce a non-fringing phase-cancelled beam for all
30 incident wavelengths and phases over a bandwidth of at
31 least 1% plus or minus the center wavelength of a
32 coherent light source such as a laser. Furthermore,
33 the device disclosed herein represents a simple and
34 reliable method for the creation of a phase-cancelled
35 collinear beam even when the source laser is of
36 relatively low quality and power and has a limited

1 coherence length. The production of such a device
2 allows research into the properties of phase-cancelled
3 collinear beams to be undertaken at moderate cost and
4 is a basis for the generation of such beams for other
5 scientific and commercial applications.

6
7 Other objects, features and advantages of the invention
8 will become apparent from a reading of the
9 specification when taken in conjunction with the
10 drawings.

11 12 BRIEF DESCRIPTION OF THE DRAWINGS

13
14 Fig. 1 is a diagrammatic cross-section of an
15 overly simplified photopolymer hologram which is
16 provided for the purpose of illustrating the potential
17 interaction of light with the differing refractive
18 indices of a photopolymer hologram as discussed in the
19 background section of the following detailed
20 description;

21
22 Fig. 2 is a flow chart of a method of producing a
23 device in accordance with the present invention;

24
25 Fig. 3 is a schematic perspective view
26 illustrating the method;

27
28 Figs. 4A and 4B are diagrammatic plan views
29 illustrating the method; and

30
31 Fig. 5 is a diagrammatic cross-section
32 illustrating a device in accordance with the invention.

33 34 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

35
36 For clarity, a brief background of lasers and holograms

1 and relevant terminology is provided.

2

3 The term "laser" is an acronym for Light Amplification
4 by Stimulated Emission of Radiation. To generate a
5 laser light source, a medium containing a distribution
6 of similar atoms in a solid or gaseous transparent
7 suspension is generally heated, or otherwise excited,
8 to produce a majority of atoms at an excited state with
9 electrons in high orbits outside the atom's "ground" or
10 unexcited state. Introduction of a beam of light into
11 the medium results in the absorption and re-emission of
12 photons from the excited atoms. Because the atoms are
13 at a threshold condition of excitation, the
14 introduction of a photon causes the atom to absorb and
15 re-emit the incident photon along with a second photon
16 of the same wavelength and phase. This process tends to
17 cause a "cascade" as each newly emitted photon
18 stimulates other atoms to absorb and emit, thus
19 amplifying the light. In an ideal world, the resulting
20 light from such a system would be coherent so that all
21 the light would be of the same phase and monochromatic
22 in that it would consist of a single wavelength. In
23 practice however, the atomic excitation is not perfect
24 and several different energy states are stimulated
25 among atoms in the suspension. This yields a narrow
26 spectrum of light, often in a temporally spaced rhythm
27 known as "mode hopping", as a majority of photons shift
28 from one wavelength to the next. For various reasons
29 the refractive index of the stimulated medium is often
30 inconstant, and the thermal excitation tends to cause
31 the phase to wander over time. The time period of such
32 wandering divided into the speed of light defines the
33 coherence length of a laser beam. This can vary
34 between a few microns to many meters depending on laser
35 type.

36

1 Holograms and their method of manufacture are well
2 known in the art. A hologram is essentially a
3 diffraction grating. A diffraction grating is created
4 when the photopolymer is exposed to a reference beam of
5 angle A and an incident beam of angle B. The
6 diffraction grating, having been created by the passage
7 of light at specific angles, tends to form as a
8 mutually interactive three dimensional lattice which
9 represents the desired fringe pattern only at a
10 specific incident angle of the replay beam. Light
11 entering the hologram with the same angle as the replay
12 or reference beam will interact with the differential
13 refractive indices of the diffraction grating and be
14 diffracted at a new wavelength dependent angle. Any
15 other angle will tend to miss the differential
16 refractive indices of the diffraction grating and
17 instead interact with the sum of the refractive indices
18 of the hologram, as if in fact the hologram were all of
19 a single average refractive index. Figure 1 shows the
20 effect: note that paths a1 and a2 pass through more or
21 less equal amounts of low (L) refractive index and high
22 (H) refractive index, whereas at a certain critical
23 angle, paths b1 and b2 pass through differential
24 refractive indices.

25
26 The efficiency of a photopolymer hologram is measured
27 by comparing the incident and non-interacted light to
28 the light that is transmitted by diffraction in the
29 intended direction of the holographic optical element.
30 The extent to which light is diffracted depends on how
31 extensive the diffraction grating is present. The
32 degree to which the diffraction grating is present is
33 dependent on the extent to which polymerization and
34 crosslinking of the holographic photopolymer is allowed
35 to proceed. Polymerization and crosslinking of the
36 photopolymer occurs when the photopolymer is exposed to

1 the light source used to create the diffraction grating
2 and during subsequent exposure to ultraviolet light and
3 thermal curing. By controlling the extent of
4 polymerization and cross-linking, one can control the
5 degree to which the diffraction grating is present and
6 thus the efficiency of the hologram. The efficiency of
7 holograms made from metal-based emulsions such as
8 silver halide can be varied by varying the grain size
9 of the emulsion.

10

11 The phenomenon of holographic efficiency is used in the
12 described device to modify the percentage of light that
13 is forced to take the phase cancelling path, since only
14 the light which passes through the differential
15 refractive indices will result in an interference
16 pattern and thus result in a diffracted path. In
17 practice the H and L portions of the hologram are less
18 well defined due to incomplete polymerisation and so
19 the efficiency is reduced even at the ideal angle as
20 explained in the polymerisation discussion above.

21

22 Also fundamental to a full understanding of the
23 invention is the phenomenon and properties of
24 refraction. As a light ray passes through two optical
25 mediums having different refractive indices and the
26 light ray is at any angle other than perpendicular
27 (normal) to the interface between the optical mediums,
28 it will undergo a change of angle becoming more acute
29 if the transition is from a lower to a higher index and
30 more oblique if the transition is from a higher to a
31 lower index. This phenomenon can be easily understood
32 if it is remembered that the higher the refractive
33 index of a medium the slower light travels through that
34 medium. Thus, as a light ray enters a medium of
35 higher refractive index at an angle, the light ray will
36 be slowed down and thus bend toward the slowed side.

1 The angle of bend is dependent on the difference in the
2 refractive indices of two optical mediums and the
3 wavelength of the incident light beam.

4
5 If a beam of light passes through an intervening
6 optical material having a different refractive index
7 compared to the refractive index of the medium the beam
8 is travelling in (an example would be light passing
9 through a window), the change in refractive index at
10 the entry to and exit from the intervening optical
11 material will be equal and opposite such that when the
12 beam enters the intervening optical material the beam
13 will bend one direction, and when the beam exits the
14 intervening optical material the beam will be bent back
15 in the opposite direction an equal amount so that the
16 entry beam and exit beam will be parallel. However,
17 the point at which the beam exits the intervening
18 optical material will be shifted laterally compared to
19 where the beam would have exited had the original entry
20 beam passed straight through the intervening optical
21 material unrefracted. The amount of lateral shift is
22 dependent on the angular shift within the intervening
23 optical material and the distance between the entry and
24 exit.

25
26 In this invention, the efficiency of a second hologram
27 is set as close to 100 % as possible and the efficiency
28 of a first hologram is set at half the efficiency of
29 the second hologram, close to 50%. When a coherent beam
30 of light of a given entry angle enters the first
31 hologram, approximately 50% of the beam will pass
32 through the first hologram affected only by the change
33 in refractive index and approximately 50% of the beam
34 will be diffracted. As both beams enter the
35 intervening optical material they encounter another
36 change in refractive index which induces a

1 wavelength-dependent change in angle for each beam. A
2 refractive index for the intervening optical material
3 is selected which induces a wavelength-dependent change
4 in refraction angle that is equal and opposite the
5 wavelength-dependent change in diffraction angle
6 induced by the first hologram so that the angles
7 mutually cancel for each wavelength of the diffracted
8 beam. Thus, the angular path of the diffracted beam
9 across the intervening optical material is essentially
10 opposite its angular path of exit from the first
11 hologram.

12
13 When the diffracted beam exits the intervening optical
14 material and enters the second hologram the change in
15 refractive index is equal and opposite the change in
16 refractive index which occurred as the diffracted beam
17 left the first hologram and entered the intervening
18 optical medium. This must be since the average
19 refractive indices of the two holograms are the same.
20 Thus, the diffracted beam will be refracted by the
21 second hologram such that its angle of departure from
22 the second hologram will be parallel to its angle of
23 departure from the first hologram (the original angle
24 of diffraction). Note that the diffracted beam would
25 have an improper entry angle with respect to the
26 diffraction grating of the second hologram and would
27 pass through the second hologram affected only by the
28 change in refractive index.

29
30 The undiffracted beam which exits the first hologram
31 passes through both the first hologram and intervening
32 optical material and into the second hologram affected
33 only by the change in refractive index. Therefore, the
34 undiffracted beam exits the intervening optical
35 material and enters the diffraction grating of the
36 second hologram by a path which is shifted laterally

1 but otherwise parallel with the path it had as it
2 entered the first hologram. Thus, the undiffracted
3 beam will have the correct entry angle to interact with
4 the differential refractive indices of the diffraction
5 grating of the second hologram. Because the second
6 hologram is close to 100% efficient, nearly all of the
7 undiffracted beam will be diffracted and thus exit the
8 second hologram parallel to the originally diffracted
9 beam.

10

11 By slight movements of the second hologram, the two
12 exit beams can be made to overlap over a large portion
13 of the diameter of their beams and the originally
14 undiffracted beam can be intercepted by the second
15 hologram such that it takes a path some multiple of a
16 half wavelength different from the path taken by the
17 originally diffracted beam. The resulting combined
18 beam will be phase cancelled for all wavelengths and
19 phases over a bandwidth of at least 1% plus or minus
20 the source center wavelength of the incident optical
21 beam.

22

23 The first and second holograms are constructed as will
24 now be described. The sequence of operations is
25 summarised in the flowchart of Fig. 2.

26

27 The diffraction grating of the first hologram is
28 created by exposing a holographic plate or film to a
29 reference beam of angle A and an incident beam of angle
30 B. In the prototype invention, an argon ion laser is
31 used as the light source, however, different lasers can
32 be used relative to the characteristics of the
33 holographic film one is using.

34

35 The laser is mounted on a laboratory optical bench and
36 a beamsplitter and mirrors are used to cause the laser

1 beam to split and project upon the holographic plate as
2 a reference beam and incident beam having the correct
3 angles. In the case of the prototype, the reference
4 beam angle was approximately 30 degrees from
5 perpendicular to the hologram and the incident beam
6 angle was approximately 2-3 degrees from
7 perpendicular. These angles can be varied as long as
8 neither beam is exactly perpendicular to the hologram
9 or so close to horizontal with the plane of the
10 hologram that the beams cannot interact with the
11 hologram to form a diffraction grating.

12
13 The efficiency of the first hologram is set close to
14 50% preferably by controlling the exposure of the
15 photopolymer to limit the polymerisation by that amount
16 or in the case of a silver halide hologram by reducing
17 the contrast to half of that achievable. By measuring
18 the difference in intensity between the output beams
19 and the input beams with a photo sensor, one can
20 determine the point at which the desired efficiency is
21 achieved. The second hologram is manufactured using
22 the same reference and incident beam at the same angles
23 but with an efficiency as near 100% as is practical or
24 to the limit achievable with a silver halide hologram.
25 Modern photopolymers typically allow an efficiency of
26 up to 97% once a series of iterative exposure tests and
27 thermal curing tests have been completed. Experience
28 shows that a consistent exposure and bake for a
29 particular photopolymer from a particular manufacturers
30 batch can be determined after a few iterations for any
31 chosen polymerisation efficiency and therefore for any
32 chosen holographic diffraction efficiency.

33
34 Since the consistency of the manufacture of
35 photopolymers is not yet ideal the calculation of
36 resultant diffraction and refraction ratios of the

1 hologram is impossible thus pre-determination of a
2 specific refractive index for the intervening optical
3 material is currently impossible. The solution to the
4 problem is to exploit the thermal curing properties of
5 photopolymers as described below.

6
7 Referring to Fig 3 and Fig 4A, a pair of lasers with a
8 wavelength difference of a few nanometers are set up to
9 provide beams 10 and 12 to a beam splitter 14, and thus
10 to produce a single collinear mixed beam 16 through an
11 oven (not shown) and thence to project at a screen or,
12 preferably, at a sensor array 18. The hologram 2
13 which is 100% efficient is placed in the path of the
14 beam 16 at point X such that the beam 16 impinges on
15 the hologram 2 at the reference angle α . Since the
16 incident beam 16 is essentially composed of two
17 different wavelengths of light and the angle of
18 diffraction for a given hologram is wavelength
19 dependent, two exit beams (20 and 22) will be produced
20 by the hologram 2. The wavelength of light in one beam
21 will be shorter than the wavelength of light in the
22 other beam and both beams will be projected on the
23 sensor array 18 as two projection points 24 and 26.
24 The difference between the centers of the two
25 projection points 24 and 26 is measured by the
26 photosensor array at point Y and recorded.

27
28 The hologram 2 is removed and replaced at X with a test
29 photopolymer 28 (Fig. 4B) which has been exposed to the
30 same total energy in Joules of incoherent light as the
31 hologram 1 has been exposed to coherent light, such
32 that the average refractive index of the test
33 photopolymer 28 equals the average refractive index of
34 the hologram 1. An intervening optical material in the
35 form of an uncured photopolymer 30 is placed between
36 the test photopolymer 28 and the sensor array 18. The

1 differential between the refractive index of the
2 hologram 2 or test photopolymer 28 and the refractive
3 index of the intervening optical material 30 will
4 define the angle of refraction for a given wavelength
5 at the interface between the first hologram 1 and the
6 intervening optical material 30 (interface 32 in Fig.
7 5), and it is this angle's dependence on wavelength that
8 this set up is designed to define.

9
10 The refractive index of the intervening optical
11 material 30 is determined by the structure and density
12 of the photopolymer which is used as to make the
13 intervening optical material 30. The structure and
14 density of this photopolymer can be varied depending on
15 the amount of light to which the photopolymer and its
16 activating dye is exposed to and also to the subsequent
17 crosslinking induced by exposure to an elevated
18 temperature. By exposing the photopolymer to a
19 suitable amount of light and then monitoring the
20 refractive index during elevated temperature curing
21 (cross linking), a specific refractive index can be
22 achieved.

23
24 The actual refractive index will change slowly
25 proportional to the time and temperature. It can be
26 frozen at a specific value by dropping the temperature
27 below a critical temperature at which cross linking
28 occurs for a given photopolymer. The process is made
29 difficult by the fact that the refractive index changes
30 in only one direction and by the fact that the curing
31 process can not be instantaneously stopped. However,
32 one can experiment with a sample of the same
33 photopolymer and by carefully observing the change in
34 angle after the temperature is dropped below the curing
35 point, one can easily see by how much in advance of the
36 desired angle the curing temperature must be reduced to

1 the critical temperature. The critical temperature of
2 the photopolymer will represent the maximum operating
3 temperature of the finished element since further
4 exposure to elevated temperatures will cause the
5 refractive index to change from the desired refractive
6 index previously established by the above-described
7 process of polymerization and cross-linking.

8
9 Almost any photopolymer of sufficient range of
10 refractive index may be used to make the intervening
11 optical material, including the same photopolymer used
12 for the production of the holograms. All that is
13 required of it is that it can be cured to a mean
14 refractive index that is different from the average
15 refractive index of the holograms and that it is
16 homotropic in that the speed of light in this material
17 is the same in all directions. Low cost photopolymers
18 such as the ultraviolet curing cements made by the
19 Lektite Corporation have been used for this purpose.
20 Generic dye activated photopolymer is also a suitable
21 material and is available from several sources. The
22 formulation can be determined from various published
23 papers on the subject.

24
25 The initial refractive index of the photopolymer which
26 is to be used for the intervening optical material 30
27 is made higher or lower than the average refractive
28 index of the hologram 1 depending on the change of
29 refractive index which is necessary to bend the
30 diffracted exit beam in the desired direction. All
31 that is important is that an initial refractive index
32 is chosen for the intervening optical material 30 such
33 that the change of refraction between the first
34 hologram 1 and the intervening optical material 30 will
35 cause the exit beam from the hologram 1 to bend back
36 opposite its path of deflection as it passes through

1 the intervening optical material. Since the
2 diffraction angle for the hologram 1 is known, a
3 photopolymer can be chosen having the necessarily
4 higher or lower initial refractive index. The
5 photopolymer to be used for the intervening optical
6 material 30 has typically been treated with sufficient
7 ultraviolet light that the photopolymer is converted to
8 a solid having an initial refractive index as
9 previously described.

10

11 The manufacture of the intervening optical material 30
12 is as follows:

13

14 Referring again to Figs. 3 and 4, the hologram 2 at
15 position X is removed and replaced with the test
16 photopolymer 28. A photopolymer which is to be used
17 for the intervening optical material 30 is prepared so
18 as to have a long dimension L and a narrow dimension M.
19 Dimension L is made equal to the distance X-Y in Figs.
20 3 and 4. Distance X-Y equals the distance between the
21 test photopolymer 28 and the sensor array 18 and is the
22 same as the distance between the hologram 1 and the
23 sensor array 18. In the prototype, a photopolymer 6 cm
24 long and 0.3 mm wide has been used to make the
25 intervening optical material 30. However, as will be
26 explained later, handling and construction
27 considerations are the main criteria for the actual
28 size of dimensions M and L.

29

30 One end of photopolymer 30 is placed in contact with
31 the sensor array and the other end is placed against
32 the test photopolymer 28 at point X (Fig. 4B) so that
33 dimension L of photopolymer 30 is perpendicular to the
34 sensor array 18.

35

36 When the pair of lasers are energized, a collinear beam

1 16 is projected into the oven through the test
2 photopolymer 28 and photopolymer 30. At the exit side
3 of photopolymer 30 the shorter wavelengths of the two
4 lasers will be laterally displaced relative to the
5 longer wavelengths such that two beams 20 and 22 will
6 exit photopolymer 30 and impinge on the sensor array 18
7 as two projection points 24 and 26 (Fig. 4B). By
8 placing photopolymer 30 with its greater dimension L
9 perpendicular to the array 18, a more easily measured
10 displacement of the projection points of the two beams
11 can be made at Y than would be the case if dimension XY
12 were to be made equal to dimension M which would be the
13 operational dimension of photopolymer 30.

14

15 Initially, ultraviolet light is used to cure
16 photopolymer 30. As photopolymer 30 cures, the
17 progressive change in the difference between the
18 centers of the projection points 24, 26 of the two
19 beams 20 and 22 can be measured at the sensor array 18.
20 Initially, the projection points 24, 26 will be close
21 together. As the curing process starts, the projection
22 points 24, 26 will begin to spread. As the distance
23 between the projection points 24, 26 begins to approach
24 the desired spread, the ultraviolet light is turned off
25 and the oven, which has been set to the photopolymer
26 manufacturer's recommended curing temperature, is
27 turned off. As previously mentioned, the curing
28 process cannot be instantaneously stopped. Therefore,
29 the oven is turned off far enough in advance such that
30 when the curing process finally stops, the centers of
31 the projection points 24, 26 will measure exactly the
32 same distance as that measured between the centers of
33 the projection points produced by the first hologram 1
34 thus establishing the refractive index of photopolymer
35 30.

36

1 At this point, the linear shift of the projection
2 points 24, 26 of the two beams 20, 22 which were
3 angularly shifted due to the change of refractive index
4 between the test photopolymer 28 and photopolymer 30 is
5 made equal to the linear shift caused by the equal but
6 opposite angular shift of the beams 20, 22 which were
7 diffracted by the hologram 1 as previously measured.
8 Thus, in the finished optical device, the change in
9 refractive index between the first hologram 1 and the
10 intervening optical material 30 will be such that the
11 wavelength-dependent variation in refraction angle
12 induced by the refractive material 30 will be equal and
13 opposite the wavelength-dependent variation in
14 diffraction angle induced by the first hologram 1 such
15 that the angles mutually cancel for each wavelength of
16 the incident optical beam.

17

18 The assembly of Fig 5 can now be made.

19

20 The intervening optical material (photopolymer 30) is
21 inserted with dimension M between the two holograms 1
22 and 2. The hologram 1 which is 50% efficient is
23 stabilized in its alignment with respect to the
24 intervening optical material. A laser beam B having
25 the correct entry angle to interact with the
26 differential refractive indices of the diffraction
27 grating of the hologram is directed at the stabilized
28 hologram 1 so two output beams, p1 and p2 of Fig. 5,
29 are produced by the optical device. Reference 34
30 indicates holographic deflection. Both beams exit the
31 intervening optical material 30 at different angles.
32 Beam p1 represents the diffracted beam.

33

34 A small dab of UV curing cement is applied to either
35 the exposed face of the intervening optical material 30
36 or the second hologram 2. As the second hologram 2 is

1 pushed up against the intervening optical material 30,
2 it is pivoted about the axis of the exiting beams until
3 beams p1 and p2 line up as a single spot on a target
4 such as a frosted glass or a CCD. Then, the second
5 hologram 2 is adjusted laterally. As the second
6 hologram 2 is moved laterally (perpendicular to
7 dimension M), the beam will be seen to modulate between
8 light and dark. Upon closer examination of the spot,
9 the two beams p1 and p2 can be seen overlapping as two
10 circles on the target. This can be facilitated by
11 magnifying the beam projection point with a lens
12 (taking the usual precautions for eye protection) or
13 connecting the CCD to a monitor.

14
15 The desired condition is to achieve both maximum
16 overlap of the beams p1 and p2 and maximum cancellation
17 simultaneously. Beam p2 which is diffracted by the
18 second hologram 2 tends to have a slightly harder edge
19 than beam p1. This makes aligning the overlap easier
20 since, in practice, beam p1 will form a slight halo or
21 "corona" around beam p2 making it easy to see when the
22 beams are ideally aligned and maximum cancellation
23 (destructive interference) has been achieved. This
24 adjustment is possible because the diameters of the
25 beams are large with respect to the wavelength and by
26 adjusting the hologram laterally, that portion of beam
27 p2 taking a path some multiple of a half wavelength
28 longer than the beam p1 can be intercepted. The
29 differential required between the two beam paths occurs
30 many times within the diameter of the combined beams so
31 the second hologram can be adjusted over several
32 destructive peaks until the best position is chosen.

33
34 Once the operator is satisfied that the optimum
35 condition is achieved, the device as a whole is exposed
36 to ultraviolet to cure the cement. Various

1 manufacturers make such cement and the ideal curing
2 exposure will be as recommended by the manufacturer of
3 the cement used.

4
5 The difference between several peak cancellations in
6 terms of beam overlap is small and so the overall
7 performance of the device will only vary a few
8 fractions of a percent from optimum even if the device
9 is quite grossly misaligned in terms of beam overlap.
10 Also, even if the cancellation point is not perfect, a
11 small adjustment in the entry angle of the replay beam
12 will correct it to some extent. For maximum
13 efficiency, the positioning of the second hologram 2
14 should be performed carefully. For example, if the
15 device is to be used as the aperture for a spatial
16 filter in a powerful laser system, it is naturally
17 important to insure that as little power as possible
18 either bypasses the arrangement or is absorbed by it.

19
20 The adjustment of the second hologram 2 can be
21 accomplished by a micromanipulator such as would be
22 used for the adjustment of a microscope stage. An
23 alternative method is to use a piezoelectric transducer
24 as a component of a suitably constructed jig. A
25 piezoelectric transducer changes dimension proportional
26 to an electric field. The holograms 1 and 2 and
27 intervening optical material 30 can be held permanently
28 in place by a clamp as an alternative to UV curing
29 cement.

30
31 Because of the relationship between the holograms 1 and
32 2 and the intervening optical material 30 it is now
33 possible to vary the incident wavelength by up to 2%
34 while still maintaining perfect temporal cancellation
35 of the beam. Actual intensity cancellation is less
36 than perfect since the holographic polymerisation or

1 halide contrast efficiencies are never perfect.

2

3 The ability of the device to cancel a wide bandwidth of
4 incident light is explained below with reference to Fig
5 5.

6

7 The wavelength of the incident light changes dimension
8 dx such that the longer the wavelength the greater dx .
9 Thus the path length of $p1$ and the path length of $p2$
10 will be wavelength dependent. By defining the mean
11 value of dx it is possible to set the difference
12 between path $p1$ and path $p2$ as an integer multiple of a
13 half wavelength for the mean wavelength of the laser.
14 If that multiple is odd, i.e. 1,3,5,7 etc., then the
15 beams of $p1$ and $p2$ will cancel. Further, since the
16 differential of $p1$ and $p2$ is defined by dx which is
17 wavelength dependent, it can be seen that the delay of
18 $p2$ can be set to consistently equal one half wavelength
19 over any wavelength that is interacting with the
20 optical device and within a range such that dx does not
21 exceed the diameter of the beams $p1$ and $p2$. Defining
22 the mean value of dx and setting the difference between
23 path $p1$ and path $p2$ as an integer multiple of a half
24 wavelength for the mean wavelength of the laser is
25 accomplished simply by making small adjustments of the
26 second hologram 2 as previously described. As the
27 correct positioning of the second hologram 2 is
28 established, the individual delay for each wavelength
29 is made proportional to its wavelength.

30

31 Dimension M is important only as to how it relates to
32 dx and so defines the mean differential path length of
33 $p1$ to $p2$. Since dx is freely adjustable, handling and
34 construction considerations are the main criteria for
35 the actual size of dimension M . As stated before,
36 dimension L which is defined by the distance XY , is

1 chosen simply to ensure that the projection points can
2 be sufficiently discriminated by the photosensor array
3 18. Dimensions M and L are therefore only so labelled
4 as to facilitate the description of the device. For
5 example, successful devices have been constructed with
6 dimension M as small as 0.05mm and as large as 1mm.
7 The CCD photosensor array used in the prototype's
8 construction was of sufficient resolution to allow
9 dimension L to be less than 10mm, and in practice any
10 commercial camera-type CCD array can be used at this
11 dimension of L.

12
13 Note that the lateral displacement of the replay beam
14 is very small with respect to beam diameter. The
15 interaction of the two beams from the second hologram 2
16 is constant in terms of wavelength displacement through
17 a wavelength variation of several percent. As the
18 angle of the replay beam is changed, the interaction of
19 the beam with the holograms changes. As the angle
20 increases, more light passes through the grating
21 without interacting. This is so because the
22 differential refractive indices that define the grating
23 are blurred by the passage of light through more than
24 one index of the film, as is crudely represented in Fig
25 1. Since the index is defined by the actual atomic
26 density averaged through the path of a ray, this
27 density varies over a very small scale. The result of
28 this is that the probability of the cancellation of the
29 beam changes from an absolute maximum defined by the
30 peak efficiency of the hologram to a minimum of near
31 random distribution. The output beam in the
32 non-cancelled condition remains polarized but is
33 reduced in coherence from the initial laser incident
34 beam. The loss of coherence is unlikely to be a
35 problem except in applications where a long range
36 projection of over two million wavelengths is needed.

1 Within one million wavelengths, focusing can be
2 achieved within a reasonable approximation of the
3 diffraction limit.

4
5 Note also that as the initial hologram passes a wave
6 through the diffraction path or the non-diffraction
7 path (depending only on the random chance of a specific
8 photon passing through a polymerised portion of the
9 hologram), a considerable portion of the delayed beam
10 might be expected to consist of photons that would lack
11 coherent partners taking the alternative path. In
12 practice, the so called quantum entanglement of photons
13 emitted from a laser source extends over a far greater
14 volume of any laser source than had been previously
15 thought. This results in the unexpected tendency of
16 the photons passing through the device to self select
17 into pairs, one taking the delayed path and one the
18 short path. Without this effect the expected level of
19 cancellation in the described device would be of the
20 order of 70%. The actual cancellation measured is
21 often greater than 98%.

22
23 That the effect is truly cancellation rather than some
24 form of absorption is readily determined by measuring
25 the temperature of an element used to intercept a laser
26 beam of known power. If the reduction of the beam
27 intensity were due to absorption, then the temperature
28 of the element would rise proportionately to the energy
29 intercepted whereas in the case of cancellation, no
30 temperature rise would be expected. Careful
31 measurements show that no such temperature rise occurs,
32 indicating that the 98% reduction in the beam intensity
33 is indeed due to cancellation alone.

34
35 Given the photon entanglement noted above, a practical
36 maximum cancellation for room temperature experiments

1 has been found to be approximately 98%. This may be
2 improved in controlled temperature applications and may
3 be reduced if the environmental temperature must vary
4 by more than ten degrees Celsius. The apparatus is
5 capable of remaining stable at power densities of
6 greater than 500 mW proving that the observed effect is
7 true collinear cancellation (If the effect was caused
8 by some misunderstood absorption phenomenon, the power
9 would be absorbed and the element would melt as
10 explained above).

11
12 The optical device as herein described serves a purely
13 practical application as an attenuator for high powered
14 lasers. Simply putting a shutter across a high powered
15 laser beam is not possible since the beam simply burns
16 through. The above device can intercept a laser beam
17 of any power and reduce its intensity by 98% without
18 itself absorbing any energy. A practical experiment
19 with a beam of 500mW has been conducted. The power
20 density of the beam being 312 W/cm^2 , the change in
21 temperature was equivalent to only 0.1 percent of the
22 incident power.

23
24 Another simple application of the optical device would
25 be the production of a spatial filter. A conventional
26 spatial filter consists of a pin hole through which a
27 laser is projected. Since the circumference of the
28 hole is subject to the full power of the laser beam,
29 the hole tends to burn away in a short time. To
30 overcome this problem, an optical device in accordance
31 with the above-described invention, could be made for
32 the particular laser and then a pinhole drilled through
33 it. When the laser beam is directed at the pinhole,
34 rather than absorbing the radiation at the edge of the
35 hole as in a conventional pinhole, all the light that
36 failed to pass through the pinhole would simply be

1 cancelled.

2

3 This optical device also makes possible the
4 construction of an achromatic optical lens whereby the
5 lens would comprise the holographic diffraction
6 gratings and refractive elements interrelated in the
7 manner disclosed in the specification. In practice, a
8 single holographic/refractive lens could not cover the
9 entire optical spectrum. However, a group of such
10 devices could cover the entire optical spectrum.
11 Although the use of photopolymers as described above is
12 the presently preferred method of implementing the
13 invention, this may be done in other ways.
14 Photographic type metal-based emulsions, such as silver
15 halide may be used to construct the holograms.
16 However, the efficiency of an optical device utilizing
17 silver halide holograms would be greatly reduced and a
18 much more powerful laser would be needed to achieve as
19 good a result as would be realized utilizing
20 photopolymer holograms and a low powered laser. An
21 emulsion may be used in conjunction with a photopolymer
22 to set the holographic efficiencies by controlling the
23 emulsion grain size. Alternatively, the holographic
24 elements may be formed by photo exposure of emulsion
25 layers, or by pressed elements produced from
26 photographic masters.

27

28 The invention has been described hereinabove with
29 reference to the use of a pair of holographic
30 diffraction gratings. It would in principle be
31 possible to achieve the benefits of the invention by
32 using different forms of diffraction grating (or other
33 optically dispersive elements) separated by an
34 intermediate member of a chosen refractive index.

35

36 Further modifications may be made to the foregoing

1 mbodiments within the scope of the present invention.

1

2 CLAIMS

3

4 1. An optical device comprising a first and a second
5 hologram, each hologram having the same diffraction
6 grating such that both holograms induce the same
7 wavelength-dependent angle of diffraction and each
8 hologram having the same average refractive index, said
9 second hologram positioned parallel to the first
10 hologram and spaced apart from the first hologram by an
11 intervening optical material of a chosen refractive
12 index, the refractive index of the intervening optical
13 material being such that a wavelength-dependent angle
14 of refraction induced by the intervening optical
15 material at the interface between the first hologram
16 and the intervening optical material is made equal and
17 opposite to the wavelength-dependent diffraction angle
18 induced by the first hologram such that the two angles
19 cancel for any given wavelength of light.

20

21 2. A device according to claim 1, in which the first
22 and second holograms have pre-determined efficiencies.

23

24 3. A device according to claim 2, in which the first
25 hologram is about half as efficient as the second
26 hologram.

27

28 4. A device according to claim 3, in which the first
29 hologram has an efficiency of about 50% and the second
30 hologram has an efficiency greater than 95%.

31

32 5. An optical device comprising a first and a second
33 hologram and an intervening optical material of a
34 chosen refractive index, each hologram having the same
35 diffraction grating such that both holograms induce the
36 same wavelength-dependent angle of diffraction and each

1 hologram having the same average refractive index,
2 said first hologram having an efficiency half the
3 efficiency of said second hologram, said second
4 hologram positioned parallel to the first hologram and
5 spaced apart from the first hologram by said
6 intervening optical material, the arrangement being
7 such that when an incident optical beam having a narrow
8 spread of wavelengths around a center wavelength enters
9 the first hologram at a given angle, the beam is split
10 into two beams which traverse the intervening optical
11 medium, enter the second hologram at different angles,
12 and exit the second hologram by collinear paths which
13 differ by some multiple of one half wavelength for all
14 incident wavelengths and phases over a bandwidth of at
15 least 1 % plus or minus the center wavelength of said
16 incident optical beam.

17

18 6. A device according to claim 5, in which the first
19 hologram has an efficiency of about 50% and the second
20 hologram has an efficiency greater than 95%.

21

22 7. An optical apparatus comprising an optical device
23 in accordance with any preceding claim, and a laser for
24 directing an incident optical beam on said device.

25

26 8. An apparatus according to claim 7, in which the
27 optical device is mounted rotatably with respect to the
28 incident beam for variation of the angle of the
29 incident optical beam with respect to the plane of
30 refraction and diffraction of the optical device.

31

32 9. A method of producing an optical device in
33 accordance with claim 5, the method comprising the
34 steps of :

35

36 a) providing a first and a second hologram, each
 hologram having the same diffraction grating such that

- 1 both holograms induce the same wavelength-dependent
- 2 angle of diffraction and each hologram having the same
- 3 average refractive index, said first hologram having an
- 4 efficiency half the efficiency of said second hologram;
- 5 b) positioning one of said holograms in the path of
- 6 a mixed beam of collinear light consisting essentially
- 7 of two different wavelengths such that two diffracted
- 8 beams exit the hologram at different angles to project
- 9 onto a photo-sensor array some distance L from the exit
- 10 side of the hologram;
- 11 c) measuring the distance between the projection
- 12 points of the two diffracted beams;
- 13 d) providing a first photopolymer having a chosen
- 14 initial refractive index and a long dimension equal to
- 15 L;
- 16 e) providing a second photopolymer having the same
- 17 average refractive index as said holograms;
- 18 f) substituting the second photopolymer at the
- 19 position of the hologram with respect to said mixed
- 20 beam;
- 21 g) positioning said first photopolymer between the
- 22 photo-sensor array and the second photopolymer so its
- 23 long dimension L is perpendicular to the array;
- 24 h) activating said mixed beam so that two refracted
- 25 beams project from said first photopolymer onto said
- 26 array;
- 27 i) adjusting the refractive index of the first
- 28 photopolymer by polymerization such that the distance
- 29 between the projection points of the refracted beams
- 30 changes;
- 31 j) stopping polymerisation at that point where the
- 32 displacement between the projection points of the
- 33 refracted beams measures the same as the displacement
- 34 measured between the projection points of the
- 35 diffracted beams;
- 36 k) removing said second photopolymer and securing it

1 to said first hologram;

2 1) positioning said second hologram at the face of
3 the first photopolymer opposite the first hologram;

4 m) directing an incident optical beam having a
5 narrow spread of wavelengths around a center wavelength
6 at said first hologram such that two exit beams are
7 produced by said second hologram;

8 n) adjusting said second hologram until the exit
9 beams maximally overlap and a position of maximum
10 cancellation is achieved; and

11 o) securing said second hologram to the first
12 photopolymer at said adjusted position.

13

14 10. A method of using an optical device to produce a
15 continuously cancelled collinear beam for all incident
16 wavelengths and phases over a bandwidth of at least 1 %
17 plus or minus the source center wavelength of an
18 incident optical beam, said method comprising the
19 following steps:

20 a) providing an optical apparatus in accordance with
21 claim 7;

22 b) energizing said laser and directing the laser
23 output beam to impinge on said optical device;

24 c) positioning said optical device to vary the angle
25 of the incident beam with respect to the plane of
26 refraction and diffraction of the optical device until
27 a position of maximum cancellation is achieved.

28

29 11. A method of producing a continuously cancelled
30 collinear beam for all incident wavelengths and phases
31 over a bandwidth of at least 1 % plus or minus the
32 source center wavelength of an incident optical beam,
33 said method consisting of the steps of:

34 a) providing a first and a second hologram, each
35 hologram having the same diffraction grating such that
36 both holograms induce the same wavelength-dependent

- 1 angle of diffraction and each hologram having the same
- 2 average refractive index, said first hologram having an
- 3 efficiency half the efficiency of said second hologram;
- 4 b) positioning one of said holograms in the path of
- 5 a mixed beam of collinear light consisting essentially
- 6 of two different wavelengths such that two diffracted
- 7 beams exit the hologram at different angles to project
- 8 onto a photo-sensor array some distance L from the exit
- 9 side of the hologram;
- 10 c) measuring the distance between the projection
- 11 points of the two diffracted beams;
- 12 d) providing a first photopolymer having a chosen
- 13 initial refractive index and a long dimension equal to
- 14 L;
- 15 e) providing a second photopolymer having the same
- 16 average refractive index as said holograms;
- 17 f) substituting the second photopolymer at the
- 18 position of the hologram with respect to said mixed
- 19 beam;
- 20 g) positioning said first photopolymer between the
- 21 photo-sensor array and the second photopolymer so its
- 22 long dimension L is perpendicular to the array;
- 23 h) activating said mixed beam so that two refracted
- 24 beams project from said first photopolymer onto said
- 25 array;
- 26 i) adjusting the refractive index of the first
- 27 photopolymer by polymerization such that the distance
- 28 between the projection points of the refracted beams
- 29 changes;
- 30 j) stopping polymerisation at that point where the
- 31 displacement between the projection points of the
- 32 refracted beams measures the same as the displacement
- 33 measured between the projection points of the
- 34 diffracted beams;
- 35 k) removing said second photopolymer and securing it
- 36 to said first hologram;

1 l) positioning said second hologram at the face of
2 the first photopolymer opposite the first hologram;

3 m) directing a incident optical beam having a
4 narrow spread of wavelengths around a center wavelength
5 at said first hologram such that two exit beams are
6 produced by said second hologram;

7 n) adjusting said second hologram until the exit
8 beams maximally overlap and a position of maximum
9 cancellation is achieved; and

10 o) securing said second hologram to the first
11 photopolymer at said adjusted position.

12

13 12. An optical device which produces a phase cancelled
14 collinear beam for all incident wavelengths over a
15 bandwidth of at least 1% plus or minus the center
16 wavelength of an incident optical beam when said
17 optical beam has a narrow spread of wavelengths around
18 a center wavelength and a given angle of entry to said
19 device.

20

21 13. A spatial filter consisting of an optical device
22 according to claim 5, said optical device having a hole
23 of the desired circumference formed through it such
24 that incident light that failed to pass through the
25 hole would simply be cancelled.

26

27 14. An optical device comprising a hologram and a
28 refractive optical material having a chosen refractive
29 index, said hologram constructed with a diffraction
30 grating that will induce a wavelength-dependent angle
31 of diffraction for an incident optical beam of a given
32 entry angle, the assembly of the hologram and
33 refractive optical material being such that the
34 wavelength-dependent variation in refraction angle
35 induced by the refractive material will be equal and
36 opposite the wavelength-dependent variation in

1 diffraction angle induced by the hologram such that the
2 angles mutually cancel for each wavelength of the
3 incident optical beam.

4
5 15. An achromatic lens comprising a first and second
6 hologram and an intervening optical material of a
7 chosen refractive index, each hologram having the same
8 diffraction grating such that both holograms induce the
9 same wavelength-dependent angle of diffraction and each
10 hologram having the same average refractive index,
11 said first hologram having an efficiency half the
12 efficiency of said second hologram, said second
13 hologram positioned parallel to the first hologram and
14 spaced apart from the first hologram by said
15 intervening optical material, the arrangement being
16 such that when an incident optical beam having a narrow
17 spread of wavelengths around a center wavelength enters
18 the first hologram at a given angle, the beam is split
19 into two beams which traverse the intervening optical
20 medium, enter the second hologram at different angles,
21 and exit the second hologram by collinear paths which
22 differ by some multiple of one half wavelength for all
23 incident wavelengths and phases over a bandwidth of at
24 least 1 % plus or minus the center wavelength of said
25 incident optical beam.

26
27 16. A method of producing an optical device in
28 accordance with claim 5, the method comprising the
29 steps of:

- 30 a) providing a first and a second hologram, each
31 hologram having the same diffraction grating such that
32 both holograms induce the same wavelength-dependent
33 angle of diffraction and each hologram having the same
34 average refractive index, said first hologram having an
35 efficiency half the efficiency of said second hologram;
36 b) providing an intervening optical material of a

1 chosen refractive index, the refractive index of the
2 intervening optical material being such that a
3 wavelength-dependent angle of refraction induced by the
4 intervening optical material is equal and opposite to
5 the wavelength-dependent diffraction angle induced by
6 the holograms such that the two angles cancel for any
7 given wavelength of light; and

8 c) securing the holograms to opposite sides of said
9 intervening optical material such that the optical
10 device produces a phase cancelled collinear beam for
11 all incident wavelengths over a bandwidth of at least
12 1% plus or minus the center wavelength of an incident
13 optical beam when said optical beam has a narrow spread
14 of wavelengths around a center wavelength and a given
15 angle of entry to said device.

16

17 17. An apparatus according to claim 8 in which the
18 degree of cancellation of the incident optical beam can
19 be varied by rotating said optical device with respect
20 to the incident optical beam such that the angle of
21 incidence is changed and an exit beam is produced
22 having a selected percentage of cancellation.

23

24 18. An optical device comprising a first wavelength
25 dispersive element, a second wavelength dispersive
26 element parallel to and spaced from the first
27 wavelength dispersive element, and an intermediate
28 member of a chosen refractive index, the arrangement
29 being such that the angle of refraction at the entry to
30 and exit from the intermediate member is equal to the
31 frequency dependent change of angle introduced by the
32 wavelength dispersive elements.

33

34 19. An optical device comprising a first diffraction
35 grating for receipt of an incident optical beam
36 comprising light having a narrow spread of frequency

1 around a centre frequency, a second diffraction grating
2 spaced from and parallel to the first diffraction
3 grating, and an intermediate optical medium occupying
4 the space between the first and second diffraction
5 gratings; the diffraction gratings being such, and the
6 thickness and refractive index of the intermediate
7 optical medium being such, that the incident beam is
8 formed by the first diffraction grating into two beams
9 which traverse the intermediate optical medium to
10 impinge upon the second diffraction grating by path
11 lengths through the intermediate optical medium which
12 differ by some multiple of one half of the wavelength
13 corresponding to said centre frequency, whereby output
14 beams are produced by the second diffraction grating
15 which are collinear but in inverse phase.
16

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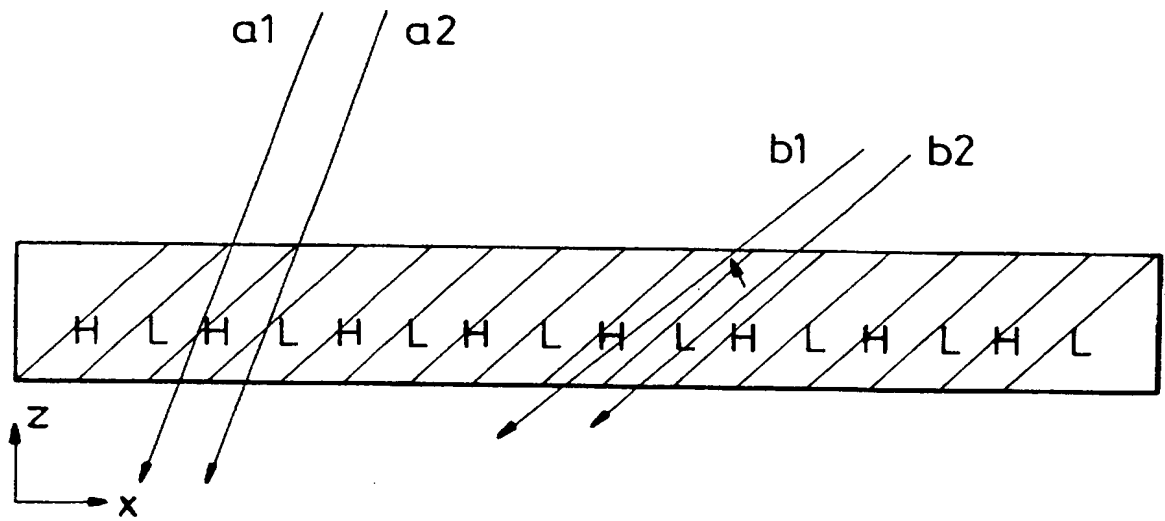


Fig. 1

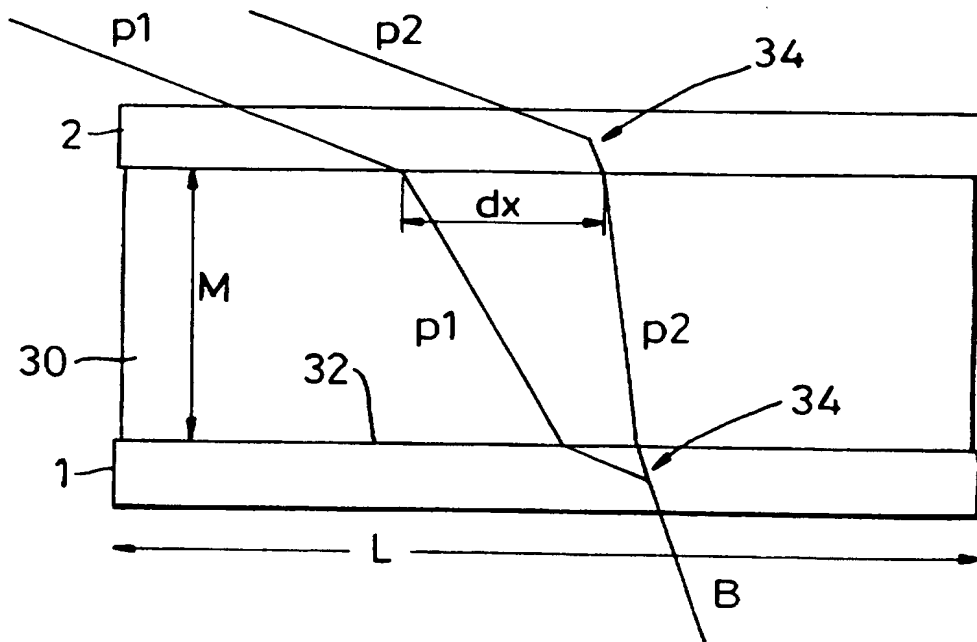
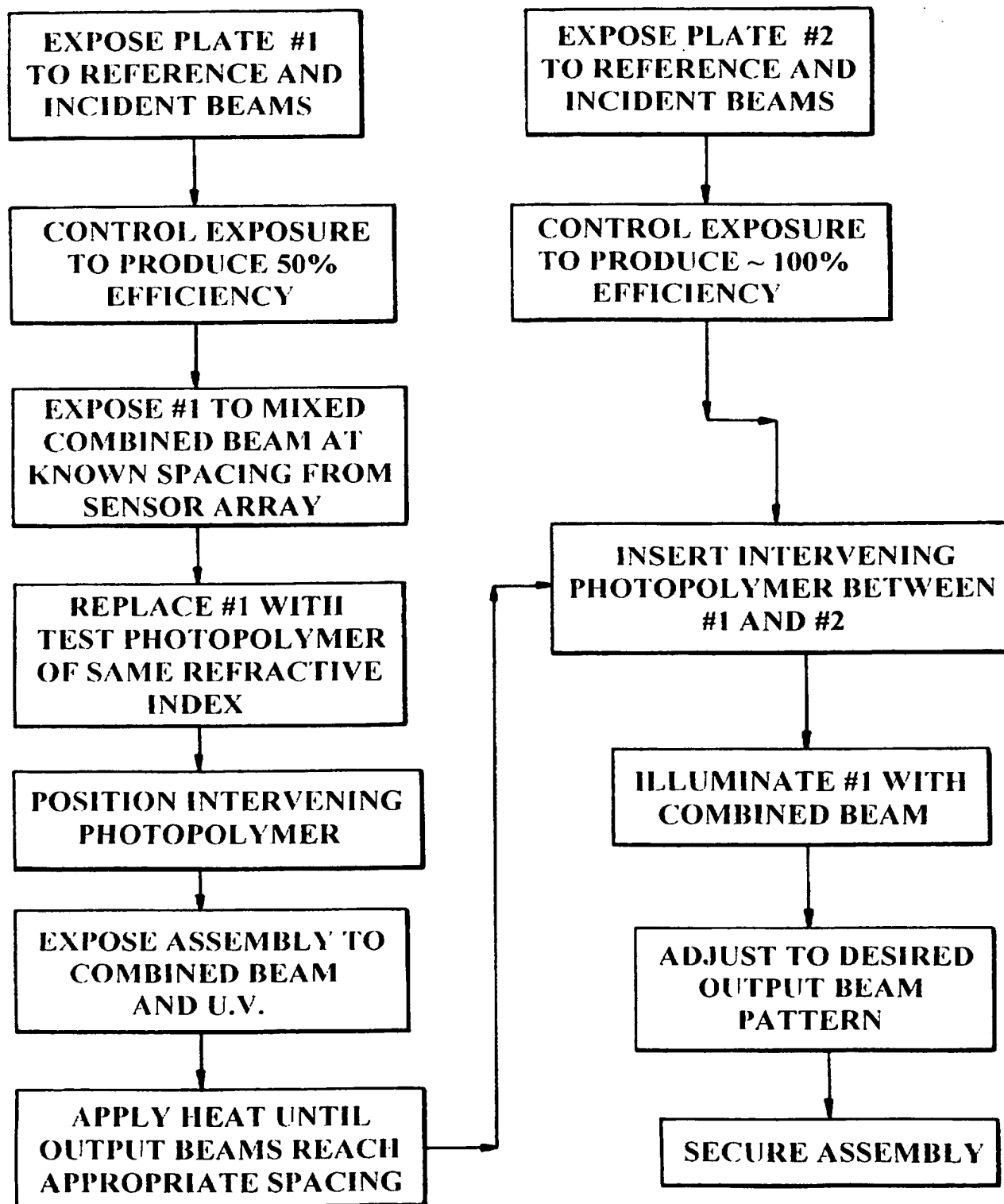


Fig 5

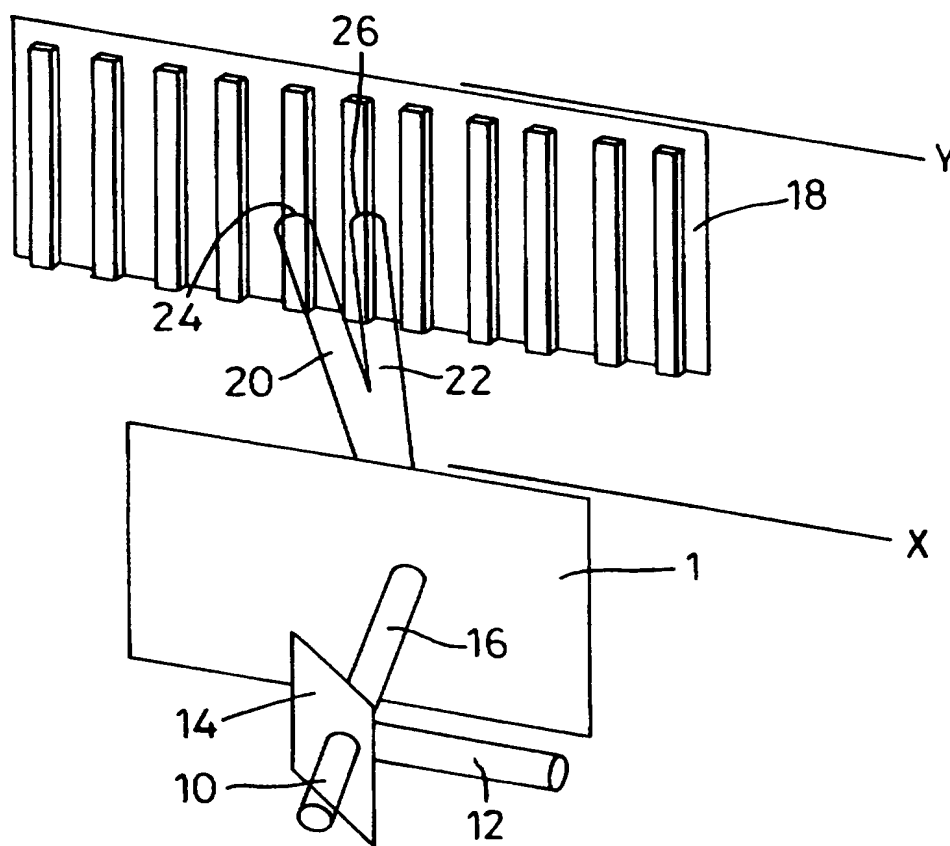
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*Fig 2*

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*Fig 3*

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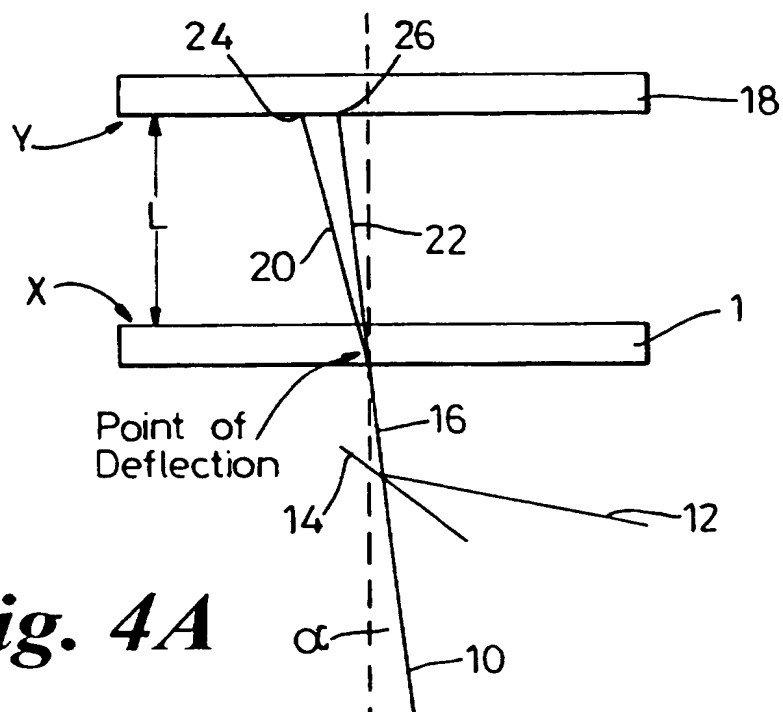


Fig. 4A

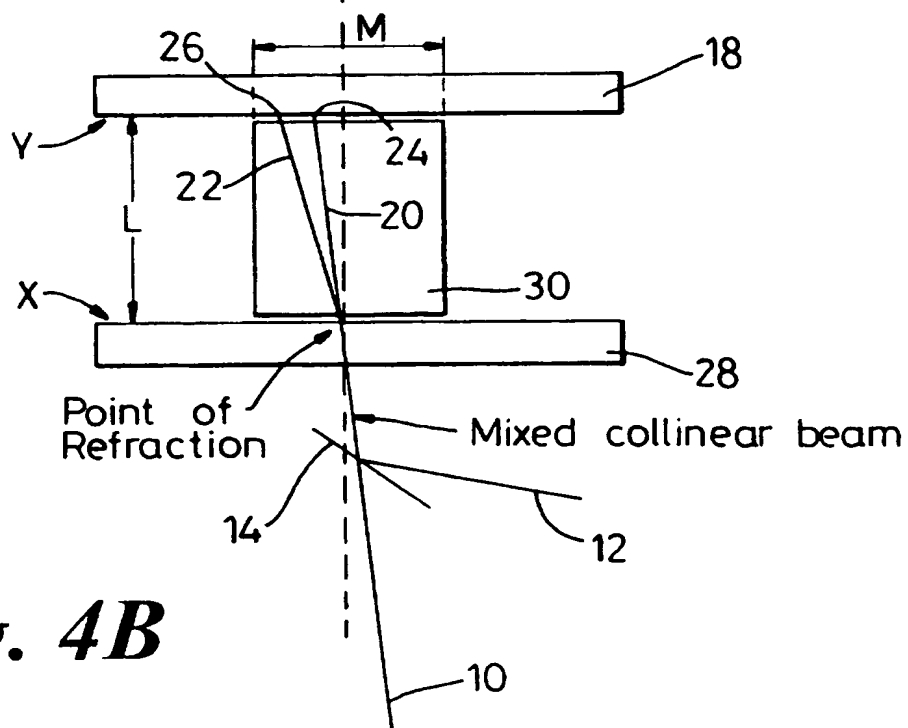


Fig. 4B

INTERNATIONAL SEARCH REPORT

International Application No

PCT/GB 96/02970

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G02B5/32 G02B5/18

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC 6 G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 243 583 A (OHUCHIDA SHIGERU ET AL) 7 September 1993	1,5,12, 14,18,19
Y	see column 5, line 62 - column 6, line 22 see column 8, line 22 - column 9, line 23; claim 1; figure 6 ---	7,9-11, 13,15,16
X	US 5 071 210 A (ARNOLD STEVEN M ET AL) 10 December 1991	1,5,12, 14,18,19
Y	see column 1, line 27 - line 64 see column 3, line 4 - column 4, line 47; claims 1-7,13-18; figure 1 ---	7,9-11, 13,15,16
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☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search

18 March 1997

Date of mailing of the international search report

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Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+ 31-70) 340-2040, Tx. 31 651 epo nl,
Fax (+ 31-70) 340-3016

Authorized officer

Hessen, J

INTERNATIONAL SEARCH REPORT

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X A	US 4 550 973 A (HUFNAGEL ROBERT E) 5 November 1985 see column 2, line 29 - column 4, line 50; figures 1,2 -----	15 1,5,7, 9-14,16, 18,19

INTERNATIONAL SEARCH REPORT

International Application No

PCT/GB 96/02970

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		JP 2267747 A	01-11-90
		JP 2292733 A	04-12-90

US 5071210 A	10-12-91	NONE	

US 4550973 A	05-11-85	NONE	
